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Microcontroller Based Proportional Derivative Plus Conditional Integral Controller for Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission Ratio Control

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Abstract. Electro-Mechanical Dual Acting Pulley (EMDAP) Continuously Variable Transmission (CVT) is a transmission utilized by electro-mechanical actuated system. It has a potential to reduce energy consumption because it only needs power during changing CVT ratio and no power is needed to maintain CVT ratio due to self lock mechanism design. This paper proposed simple proportional derivative plus conditional integral (PDCI) controller to control EMDAP CVT ratio which can be simply implemented on a microcontroller. This proposed controller used Astrom-Hagglund method and Ziegler-Nichols formula to tune PDCI gain. The Proportional Derivative controller is directly activated from the start but Integral controller is only activated when the error value reaches error value setting point. Simulation using Matlab/Simulink software was conducted to evaluate PDCI system performance. The simulation results showed PDCI controller has ability to perform maximum overshoot 0.1%, 0.001 steady state error and 0.5s settling time. For clamping condition, settling time is about 11.46s during changing ratio from 2.0 to 0.7, while for release condition, settling time is about 8.33s during changing ratio from 0.7 to 2.0.

1. Introduction

Continuously Variable Transmission (CVT) has a potential in saving fuel consumption because its wide variable ratio coverage enables the engine to run at either its fuel-efficient operating point or its maximum under various load condition [1]. Common CVT which widely used in the market is hydraulically actuated type. It needs continuous power to supply force to maintain the desired ratio and preventing gross belt slip. Thus, it can reduce CVT efficiency [2]. In order to increase CVT efficiency, Electro-Mechanical Dual Acting Pulley (EMDAP) CVT, which designed and developed by Drivetrain Research Group (DRG) Universiti Teknologi Malaysia (UTM), was introduced. EMDAP CVT has a potential to reduce energy consumption because it only needs power during changing CVT ratio and no power is needed to maintain CVT ratio due to self lock mechanism design. It utilizes two DC motors as actuator, power screw mechanism (PSM) and two moveable sheaves on both primary and secondary pulleys. Two moveable sheaves move identically to keep the belt align in the center thus, eliminate belt misalignment [3].

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A good controller is also important in order to achieve high efficiency of EMDAP CVT. By controlling two DC motors precisely and accurately, desired CVT ratio can be achieved. More than 90% industrial controller used today is Proportional, Integral and Derivative (PID) controller. PID controller is easily tuned and combined to obtain the optimal performance. Its parameters can be set independently. Thus, PID becomes the simplest and most efficient controller [4]. The success reason of standard PID controllers is the tuning rules [5]. Ziegler–Nichols method is the most famous method in tuning PID parameters. This method has good load disturbance attenuation but shows unsatisfactory performance, with a large overshoot and long settling time [6].

Recent research in controlling EMDAP CVT ratio used PD controller then fine tuned by fuzzy controller. The integral gain was not used since it caused a big overshoot [7]. Since the fuzzy controller needs complex algorithms, which is consist of fuzzification, inference, rules and defuzzification processes, it needs a bigger memory size and longer processing time when it is implemented on a microcontroller. Thus, this paper proposes a simpler proportional derivative controller then fine tuned by conditional integral controller to control EMDAP CVT ratio so that it can be simply implemented on a microcontroller. In this paper, a simulation of proportional derivative plus conditional integral (PDCI) controller was conducted using Matlab/Simulink software to evaluate PDCI controller performances, including maximum overshoot, steady state error and settling time.

2. System modeling

Basically, EMDAP CVT consists of Metal pushing V-belt (MPVB), primary and secondary pulley, power screw, helical gear, pinion gear, gear reducer and DC motor. EMDAP CVT structure is shown in figure 1.

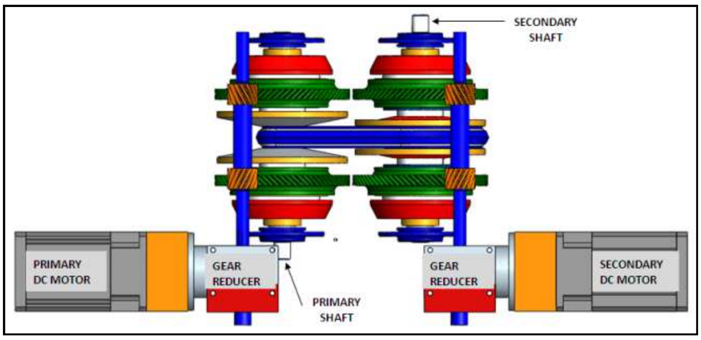

Figure 1. EMDAP CVT structure.

MPVB is used to transfer torque from primary pulley to secondary pulley. It also enables changing pulley contact radius by shifting up to increase the contact radius or by shifting down to decrease it. This system also utilizes dual acting pulley on both primary and secondary shafts. Each pulley consists of two moveable sheaves. These moveable sheaves are driven by axial movement of power screws which supply tangential force for clamping or releasing the belt. Helical gear is used to transfer torque from the pinion to the power screw, while the pinion gear receives the torque from the DC motor through gear reducer. Utilization of two moveable sheaves pulley enables to eliminate belt misalignment. Since the power screw utilizes square thread, it provides self locking mechanism which enables the system to maintain constant ratio without consuming energy. Therefore, this system only consumes energy during changing ratio [8].

2.1. DC motor modeling

DC motor transfer function model is created by determining DC motor block diagram and its parameters. DC motor block diagram is determined based on its basic equations, whereas DC motor parameters are identified based on datasheet. Equivalent model between electrical and mechanical relationship is shown in figure 2 [9].

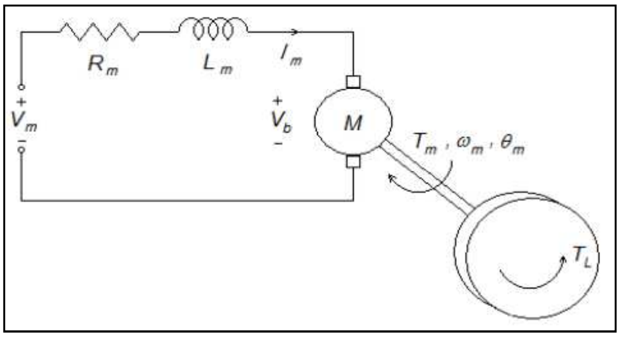

Figure 2. Equivalent DC motor model.

Transfer function of DC motor model is described as:

$$\omega_m = \left(\frac{(V_m - K_e\,\omega_m)}{(s\,L_m + R_m)} K_T - T_L \right) \frac{1}{(s\,J + B)} \tag{1}$$

Where:

ω_m	=	Motor Angular Speed	(rad/s)
V_m	=	Motor Voltage	(V)
V_b	=	Back EMF Voltage	(V)
I_m	=	Motor Current	(A)

The DC motor transfer function model is created based on equation (1) as shown in figure 3.

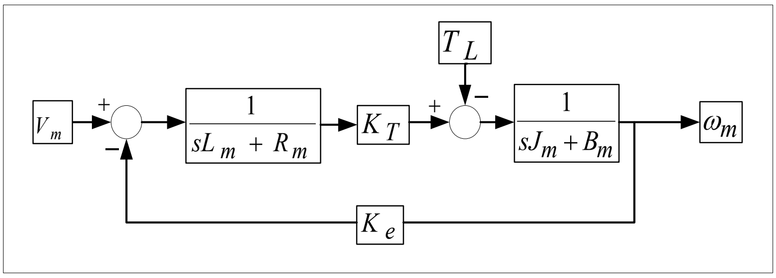

Figure 3. DC motor transfer function model.

Its parameters are shown in table 1.

Table 1. DC motor parameters values.

Parameters	Symbol	Value	Unit
Inductance	L_m	0.0228	H
Resistance	R_m	0.327	Ω
Back EMF constant	K_e	0.0535	V.s / rad
Torque Constant	K_T	0.0535	Nm / A
Rotor Inertia	J_m	7×10^{-5}	Kgm^2
Friction Coefficient	B	0.00166	Nm.s / rad

2.2. Mechanical modeling

Mechanical model consists of PSM and gear reducers models as shown in figure 4. Torque of power screw depends on clamping or release condition as represented by clamping or release equation. A condition selector is used to decide whether it is clamping or releasing. Then, the torque of power screw is transferred through interaction of helical and pinion gears. Both gears act as gear reducer. Next, torque of pinion gear is transferred to motor gear reducer. This torque of gear reducer acts as load torque for the DC motor.

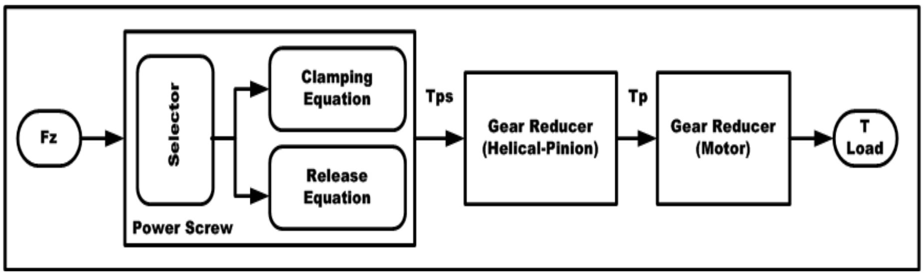

Figure 4. Mechanical model.

EMDAP CVT system utilizes PSM to convert rotational to axial movement. PSM schematic diagram is shown in figure 5. This design enables to convert 1 Nm torque of DC motor to approximately 20 kN of clamping force on MPVB [8]. Torque from DC motor is transferred to the pinion gear through gear reducer in order to produce bigger torque. Then, this torque is transferred to the helical gear and causes the helical gear to rotate. The helical gear rotation, either clockwise or counter clockwise, results the power screw movement, either inward or outward. As power screw moves, pulley sheaves also move in the same direction. The movements of pulley sheaves cause the metal pushing V-belt (MPVB) to shift up or down. The condition when the MPVB shifts up is called clamping condition. Otherwise, it is called release condition.

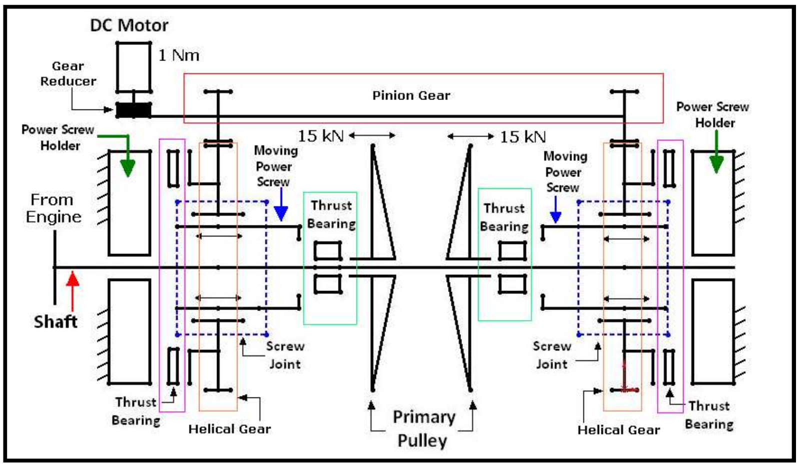

Figure 5. Power screw mechanism schematic diagram.

Torque of power screw for clamping condition is defined as:

$$T_{ps_C} = F_z \frac{d_p}{2} \frac{(\mu \pi d_p + \mathrm{L})}{(\pi d_p - \mu L)} \tag{2}$$

Whereas torque of power screw for release condition is defined as:

$$T_{ps_R} = F_z \frac{d_p}{2} \frac{(\mu \pi d_p - L)}{(\pi d_p + \mu L)} \tag{3}$$

Where:

F_z	=	Force for clamping or release MPVB	(N)
T_{ps_C}	=	Torque of power screw for clamping MPVB	(Nm)
T_{ps_R}	=	Torque of power screw for releasing MPVB	(Nm)

Dimensions of mechanical system are listed in table 2.

Table 2. Mechanical system dimensions.

Parameters	Symbol	Value	Unit
Pitch length	L	0.002	m
Pitch diameter of inner screw thread	d_p	0.0885	m
Friction coefficient	μ	0.15	
Motor Gear reducer ratio	GR_m	30:1	
Helical gear teeth	t_H	60	
Pinion gear teeth	t_P	14	

Combination of DC motor and mechanical models yields EMDAP CVT model as shown in figure 6. This model represents primary or secondary pulley system. Mechanical system acts as a load to the DC motor. The input of DC motor is motor voltage, whereas the output is motor speed.

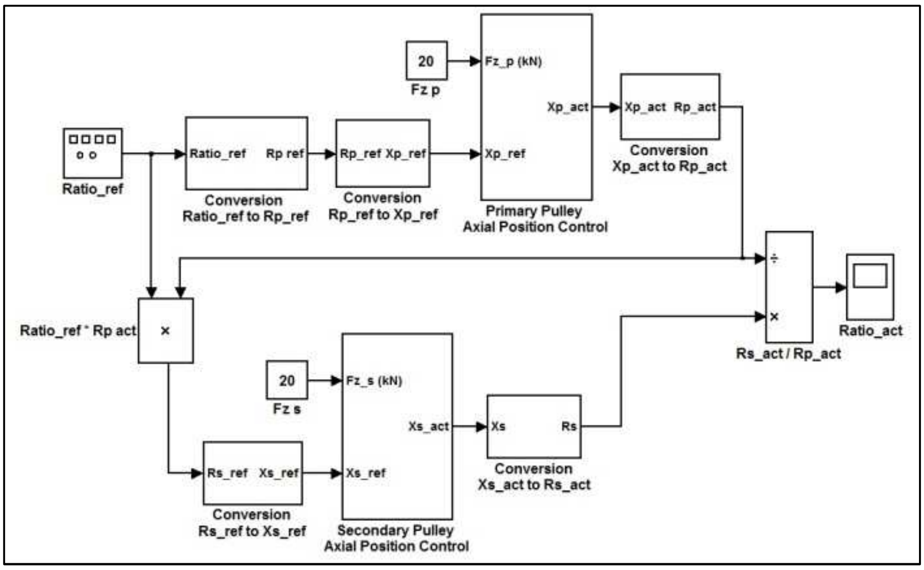

Figure 6. EMDAP CVT model.

2.3. *CVT Ratio Variator Modeling*

CVT variator consists of a primary pulley, a secondary pulley and a MPVB. CVT variator geometry diagram is shown in figure 7. By assuming that belt has a fixed length, does not slip and moves at perfect circles with primary radius, R_p, and secondary radius, R_s, the linear velocities of both pulleys and belt will be the same.

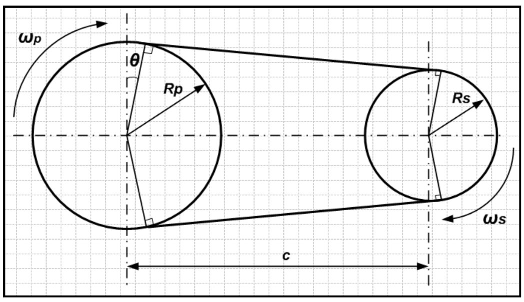

Figure 7. CVT variator geometry diagram.

Since the primary pulley is the driver whereas secondary pulley is the driven, speed and transmission ratios are the same and defined as:

$$r_s = \frac{\omega_p}{\omega_s} \tag{4}$$

$$r_{cvt} = \frac{R_s}{R_p} \tag{5}$$

Where:

r_{cvt}	=	CVT ratio	
r_s	=	speed ratio	
ω_p	=	angular speed of the primary pulley	(rpm)
ω_s	=	angular speed of the secondary pulley	(rpm)
R_s	=	secondary pulley radius	(mm)
R_p	=	primary pulley radius	(mm)

Geometric relationship between belt length and pulley radii is defined as:

$$R_p = R_s + c.sin\,(\theta) \tag{6}$$

$$L = (\pi + 2.\theta).R_p + (\pi - 2.\theta)\,R_s + 2.c.\cos\,(\theta) \tag{7}$$

Where:

L	=	belt length	(mm)
c	=	pulley center distance	(mm)
θ	=	wrapped angle on the primary pulley	(rad)

Since the pulley driver is the primary side, radius of primary pulley becomes reference in changing CVT ratio. By substituting equations (5) and (6) to equation (7), primary radius is calculated as:

$$\boldsymbol{R_p} = \frac{L-\left(\pi-2.\arcsin\left\{\frac{(1-r_{cvt}).R_p}{c}\right\}\right).r_{cvt}.R_p-2.c.\cos\left(\arcsin\left\{\frac{(1-r_{cvt}).R_p}{c}\right\}\right)}{\left(\pi+2.\arcsin\left\{\frac{(1-r_{cvt}).R_p}{c}\right\}\right)} \tag{8}$$

According to EMDAP CVT design, the belt length, L, is 645.68 mm while the center distance between primary and secondary pulley, c, is 165 mm. By varying CVT ratio from 0.7 up to 2.0, relationship among R_p, R_s and CVT ratio is plotted as shown in figure 8.

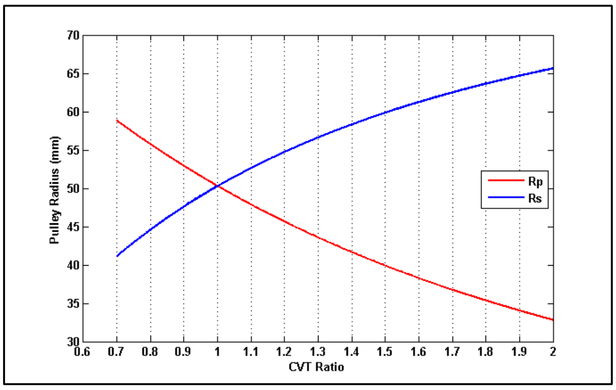

Figure 8. Relationship among CVT ratio, R_p and R_s.

2.4. Relationship between pulley radius and axial position

According to equation (5), CVT ratio is determined by both primary and secondary pulley radii. Pulley radius is calculated by considering pulley shaft diameter, R_{shaft}, sliding distance between pulley and shaft, *d,* contact point distance between belt and pulley sheave, *h*, pulley sheave angle, *α*, also effective pulley radius, *dR,* as described in figure 9. Since *x* is pulley axial position, while R_{shaft} (17.5mm), *d* (0.5mm), *α* (11o) and *h* (5.3mm) are constant, pulley radius is defined as:

$$R = R_{shaft} + d + h + \left(\frac{x}{\tan(\alpha)}\right) \tag{9}$$

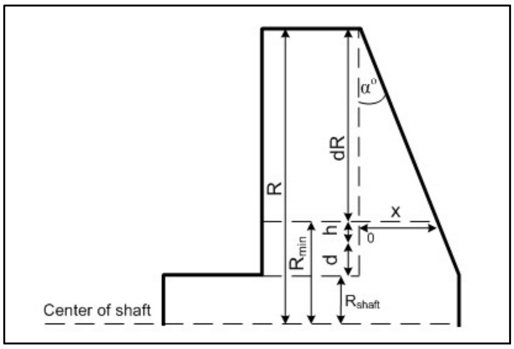

Figure 9. Relationship between pulley radius and axial position.

2.5. *CVT Ratio Control Modeling*

According to equation (9), changing pulley axial position means changing pulley radius, whereas according to equation (5), changing pulley radius means changing CVT ratio. Therefore, changing CVT ratio can be conducted by changing pulley axial position. Based on this condition, controlling CVT ratio can also be conducted by controlling pulley axial position. Pulley axial position controller is created by completing EMDAP CVT model with PID or relay feedback controller model as shown in figure 10.

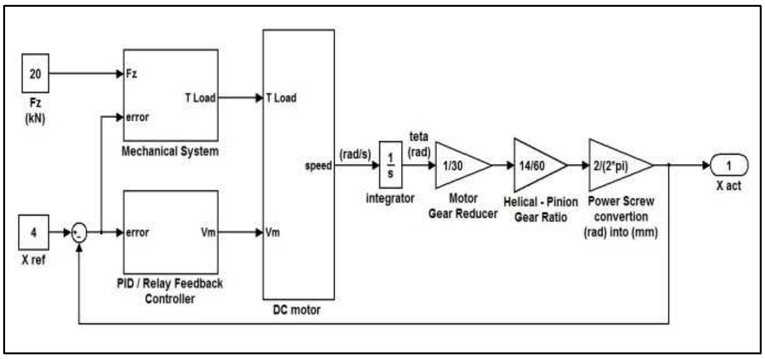

Figure 10. Pulley axial position control model.

In order to simulate EMDAP CVT ratio controller, CVT variator, axial position controllers for both primary and secondary pulleys, radius to axial position converter, and axial to radius converter models are combined as shown in figure 11.

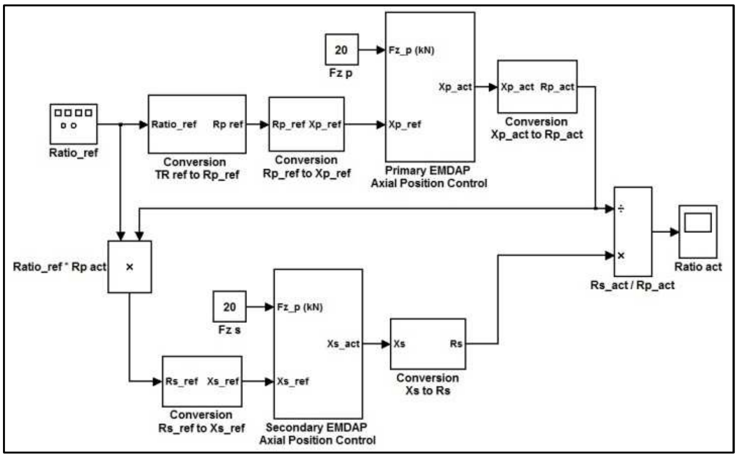

Figure 11. EMDAP CVT ratio controller model.

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Primary pulley acts as reference for changing EMDAP CVT ratio. Once the CVT ratio input is set, it is converted to reference R_p and then, it is converted again to reference x_p as desired value for controlling primary pulley axial position. The result of pulley axial position control is actual x_p. Then, it is converted to actual R_p. It is multiplied with CVT ratio input to yield reference R_s. Then, it is converted to reference x_s as desired value for controlling secondary pulley axial position. The result of pulley axial position control is actual x_s. Then, it is converted to actual R_s. By dividing actual R_s with actual R_p, the actual CVT ratio is obtained.

3. Control method

3.1. Basic PID Controller

PID controller is a famous control method which has been widely used in control process. A PID controller involves three terms: the proportional gain, K_p, integral gain, K_i, and derivative gain, K_d. Transfer function of a PID controller has the general form as:

$$G_C(s) = K_p + \frac{K_i}{s} + K_d.s \tag{10}$$

Integral and derivative gains are also expressed as:

$$K_i = \frac{K_p}{T_i} \tag{11}$$

$$K_d = K_p.T_d \tag{12}$$

A common tuning method for determining PID parameters is Ziegler-Nichols frequency response method. It is conducted by generating oscillation response of system output. To generate oscillation, Astrom-Hagglund relay feedback method gives an advantage of less tuning time than manual tuning. A typical relay feedback signal is shown in figure 12.

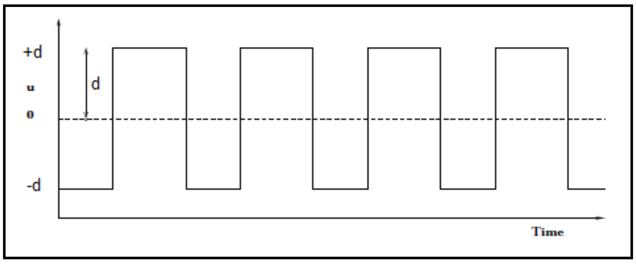

Figure 12. Relay feedback signal.

Once the oscillation generated, ultimate period, T_u, and oscillation amplitude, A, can be measured as shown in figure 13.

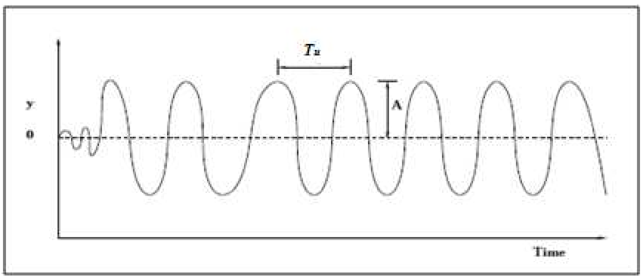

Figure 13. System output oscillation response.

The ultimate gain, K_u, can be calculated as:

$$K_u = \frac{4d}{\pi A} \tag{13}$$

Then, PID parameters can be calculated using Ziegler-Nichols formula as shown in table 3.

Table 3. Ziegler-Nichols formula frequency response.

Controller	K	T_i	T_d
P	$0.5K_u$		
PI	$0.4K_u$	$0.8T_u$	
PID	$0.6K_u$	$0.5T_u$	$0.125T_u$

3.2. *PDCI Controller*

This paper proposes Proportional Derivative plus conditional Integral (PDCI) controller for controlling primary and secondary pulley axial position. PDCI controller is used to minimize the overshoot, steady state error and settling time for clamping and release conditions. PDCI controller scheme is shown in figure 14.

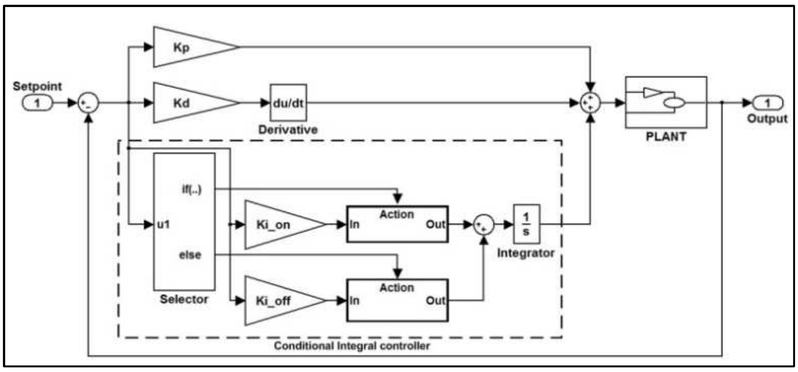

Figure 14. PDCI controller scheme.

Basically, PDCI controller consists of PD controller plus conditional integral controller. At first, PD controller is activated to control pulley axial position. When steady state error occurs, conditional integral controller is activated. This method is used to avoid a huge overshoot, steady state error and long settle time when integral controller is activated from the start. Conditional integral controller is activated based on error value setting using if-else selector. If the error meets the condition, the "if action block" is activated, the "else action block" is deactivated and the integral controller gain is set to Ki_on, which its value will be determined based on PID parameters tuning using Ziegler-Nichols and Astrom-Hagglund relay feedback methods. Thus, the output of integral controller equals to error value multiplied by integral controller gain. Otherwise, if the error doesn't meet the condition, the "else action block" is activated, the "if action block" is deactivated and the integral controller gain is set to Ki_off, which its value is 0. Thus, the integral controller output equals to zero, which means the integral controller is not used and only PD controller is activated for controlling the pulley axial position.

4. Results and discussion

In this simulation, DC motor parameters are shown in table 1 and mechanical parameters are shown in table 2. Astrom-Hagglund relay feedback controller is used to tune PID parameters. Since the DC motor operates at ±24V, the amplitude of relay feedback controller is set to ±24V. Desired axial position is set to 4 mm, which is the center of pulley axial position, while the clamping force, F_z, is set to 0, which means there is no clamping force.

According to the system output response, the values of T_u, A and d are 0.14 s, 0.0315 and 24, respectively. Based on equation (13), the value of K_u is 970.58. Then, by using Ziegler-Nichols formula as shown in table 3, PID parameters values are obtained as follow: K_p= 582.05, K_i= 8315.03, K_d = 10.18. These parameters value then, implemented to basic PID controller scheme. After all PID parameters are set, simulation is run and the result is shown in figure 15.

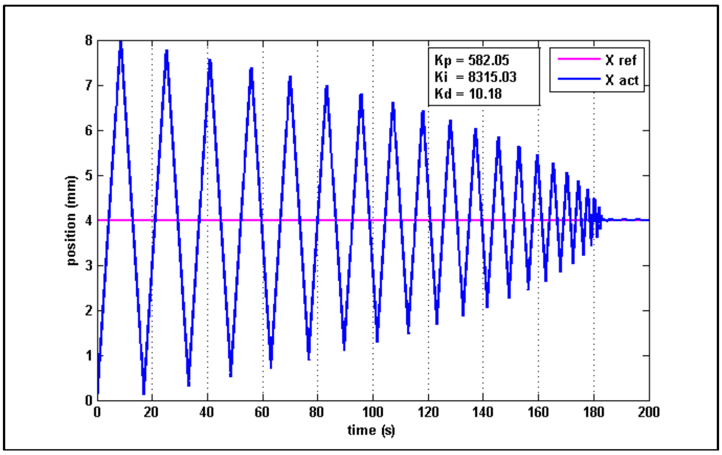

Figure 15. PID output response.

System output response shows a huge overshoot up to 100%, long settling time up to 183s and small error steady state. According to individual effect of increasing PID parameters [10], the factor which causes big overshoot and long settling time is the huge integral controller gain. Manual tuning by setting the same Kp and Kd and decreasing Ki, the system output response becomes better as shown in figure 16.

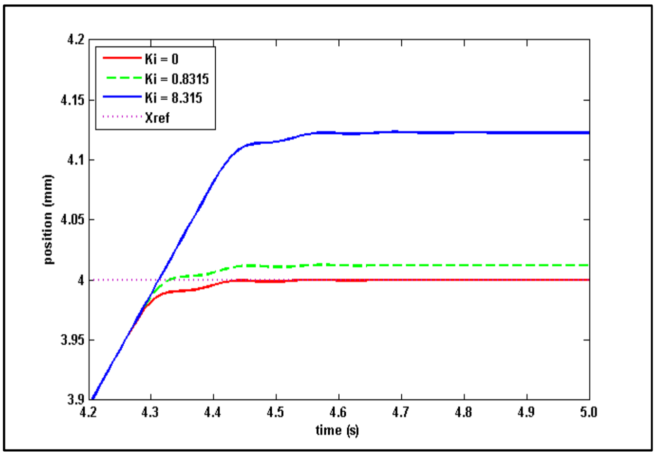

Figure 16. PID output response with manual tuning of Ki.

The smaller the integral gain, the better the system output response. No overshoot, quick settling time and no error steady state conditions can be achieved by setting integral gain to zero, which means it only uses PD controller.

Then, the PD controller is tested by applying clamping force, Fz, to the system, which is set to 5 kN, 10 kN, 15 kN and 20 kN. PD controller output response is shown in figure 17.

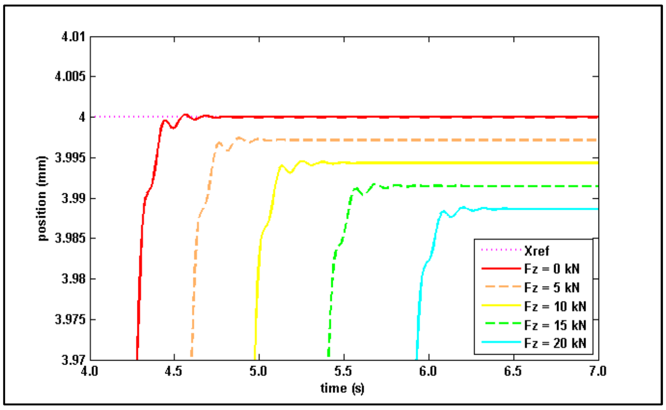

Figure 17. PD Output Response with Various F_z

Figure 17 shows that the bigger the clamping force, F_z, the longer the settling time and the bigger the steady state error although there is no overshoot in any clamping force. To eliminate this steady state error, integral controller should be conditionally activated in order to prevent a huge overshoot and long settling time. Thus, PDCI controller is designed to solve this problem. Parameters of PDCI controller are the same with PID controller which has been tuned using Ziegler-Nichols and Astrom-Hagglund methods. The only difference between PID and PDCI controller is the activation of integral controller.

Conditional integral controller is activated based on error value setting using if-else selector. If the error meets the condition, the “if action block” is activated, the “else action block” is deactivated and the integral controller gain is set to 8315.03, Otherwise, if the error doesn’t meet the condition, the “else action block” is activated, the “if action block” is deactivated and the integral controller gain is set to 0. With the setpoint 4 mm and load 20 kN, the maximum steady state error shown in Figure 17 is 0.011. By using this steady state error value, the “if condition” is set to “$-0.011 \leq$ error ≤ 0.011”. Since there is still steady state error, the “if condition” is set to several error values and the responses are shown in Figure 18 while its values are shown in table 4.

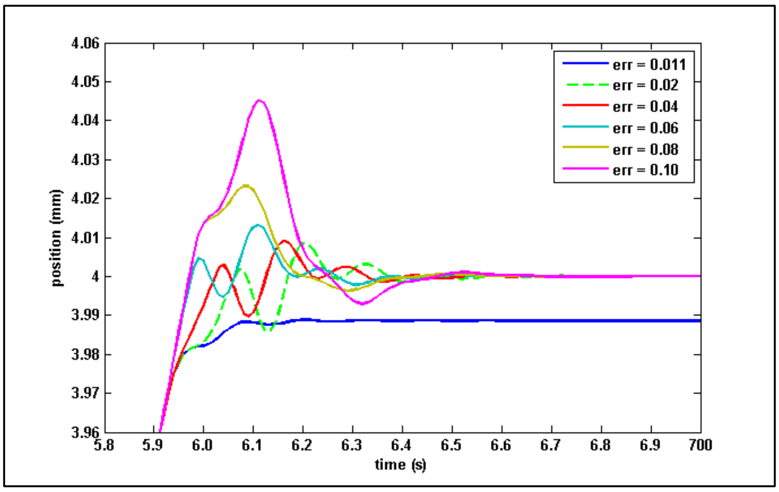

Figure 18. PDCI output response with various error setting.

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Table 4. Maximum overshoot and time settling values.

Error Setting	Max Overshoot (%)	Settling Time (s)	Steady state error (mm)
0.011	0	6.1	0.011
0.02	0.200	6.4	0
0.04	0.225	6.4	0
0.06	0.325	6.4	0
0.08	0.575	6.4	0
0.10	1.125	6.4	0

Error setting 0.02 is chosen because it has zero steady state error, 6.4s settling time and 0.2% maximum overshoot. Then, PDCI controller is tested by applying various clamping force. The results are shown in figure 19. All responses show zero steady state error and maximum overshoot less than 0.25%.

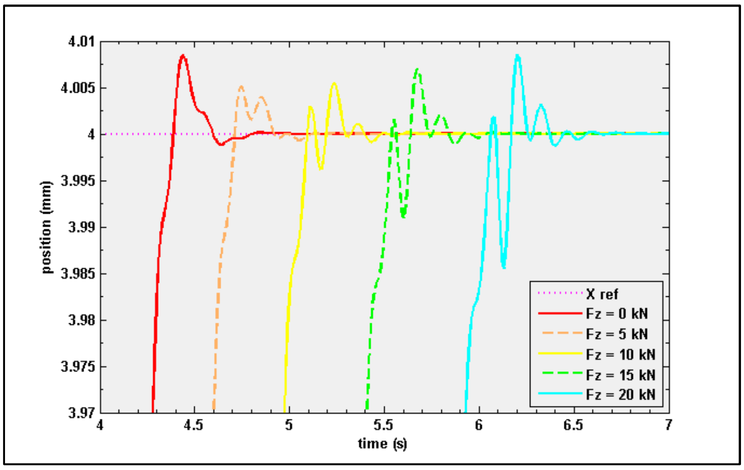

Figure 19. PDCI output response with various F_z.

By using PDCI controller for controlling both primary and secondary pulley axial position, EMDAP CVT ratio control is conducted based Matlab/Simulink model as shown in figure 11. By applying square wave input signal, which represents CVT ratio changing from 0.7 to 2.0, EMDAP CVT ratio controller response is shown in figure 20. For clamping condition, time taken to change CVT ratio from 0.7 to 2.0 is 11.46s and maximum overshoot is about 0.15% as shown in figure 21. For release condition, time taken to change CVT ratio from 2.0 to 0.7 is 8.33s and maximum overshoot is about 0.15% as shown in figure 22. Steady state error for clamping or release condition is less than 0.001.

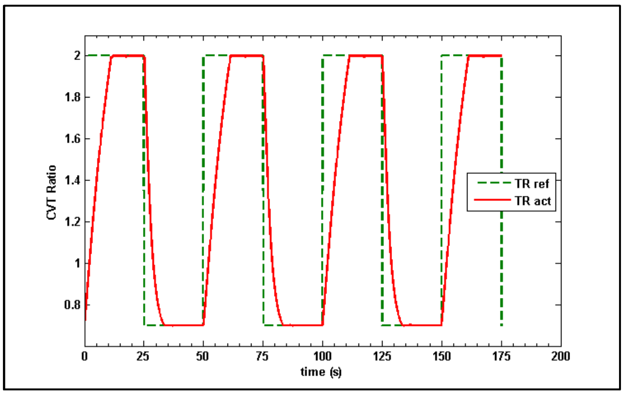

Figure 20. Output response of EMDAP CVT ratio control.

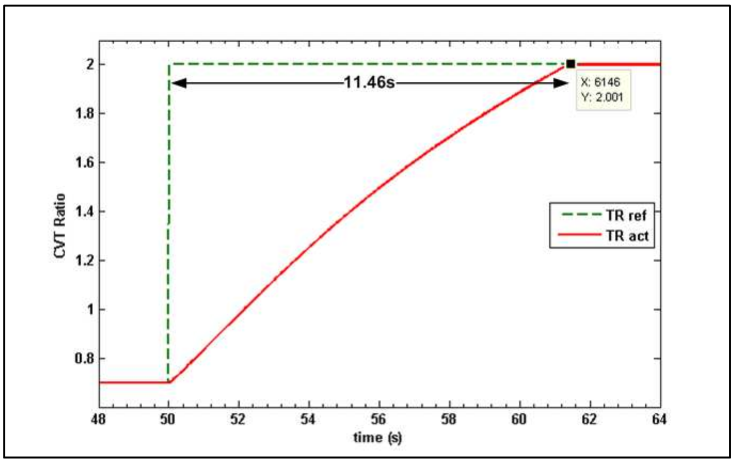

Figure 21. Output response of EMDAP CVT ratio control for clamping condition

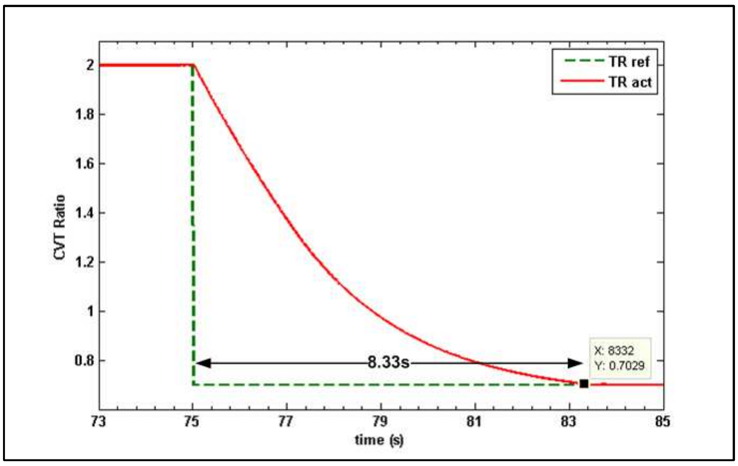

Figure 22. Output response of EMDAP CVT ratio control for release condition

5. Conclusion

Modification of PID control scheme, from basic PID to PDCI schemes, yields a good performance of PID control. By conditionally activating the integral controller, maximum overshoot is about 0.15% and transient response is about 0.5s. For clamping condition, settling time is about 11.46s, while for releasing condition, settling time is about 8.33s. Steady state error of CVT ratio is very small, less than 0.001. This PDCI controller scheme is possible to simplify the programming algorithm using C language on microcontroller for controlling EMDAP CVT ratio.

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